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Automatic Real-Time Extinction Measurement

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FOR THE COMMANDER

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AUTOMATIC REAL-TIME EXTINCTION MEASUREMENT

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ABSTRACT

We have developed a technique for measurement of atmospheric extinction at the ETS. The technique is designed to best serve the needs of ETS operations and to provide for a high degree of automation. In parallel, a software package to control the equipment and to reduce the data in real-time has been developed.

I. INTRODUCTION

One of the missions of the GEODSS ETS is the acquisition of accurate photometric data on a number of artificial satellites. In order to accomplish this, it is necessary to accurately correct for extinction by the Earth's atmosphere. It is also useful to be able to obtain values for the brightness of the night sky to aid in evaluation of system performance. This Report describes the system we have developed at the ETS to make these measurements.

The problem of atmospheric extinction is well understood, and people involved in astronomical photometry have developed techniques for making highly accurate extinction corrections. The goal of astronomical photometry, however, is somewhat different from the goal of photometry at the ETS. Astronomical objects are typically stable or rather slowly changing, and thus astronomers can reject nights of poor observing conditions. Their goal is to obtain data of the highest possible quality under excellent conditions. ETS observations, in contrast, fall into the category of transient event measurements. The ETS goal must be, therefore, to obtain data of sufficient accuracy for their use under as wide a range of observing conditions as possible.

II. ATMOSPHERIC EXTINCTION MODEL

The exact solution of the radiative transfer problem through the Earth's atmosphere is highly complicated and involves quantities which are not generally measurable. Fortunately, a very simple model gives excellent accuracy in many situations. In this model the atmosphere is treated as a finite plane parallel sheet of absorbing material in which all properties are functions of wavelength and height only. Since extinction is an exponential process, we can write the ratio of the intensity of the object at the Earth's surface (I) to the intensity outside the atmosphere (I_o)

$$I/I_o = e^{-K\ell},$$

where K paramerizes the absorptivity of the atmosphere and ℓ is the path length through the atmosphere. Expressing the absorption in astronomical magnitudes inside (m) and outside (m_o) the atmosphere gives

$$m - m_o = \frac{2.5}{\log e} K\ell.$$

It is convenient to rewrite this as

$$m - m_o = kX,$$

where

$$k = \frac{2.5}{\log e} K\ell_o$$

$$X = \ell/\ell_o$$

and ℓ_o is the thickness of the absorbing layer. For values of X near 1 (near the zenith), X can be well approximated by the secant of the zenith distance (sec z). Lower in the sky X is better represented by a simple polynomial in sec z. This approximation breaks down for X larger than about 5 (or zenith distance greater than 80^o), but this low in the sky other problems usually turn

out to be more important.

This model can now be used to evaluate k *via* observation of a steady extra-atmospheric source, say a star. For example, if a star is observed twice at two different zenith distances, different magnitudes will result:

$$\delta m = \partial A/\partial k \; \delta k = \partial A/\partial X \; \delta X$$

where A is the atmospheric absorption. If all our assumptions about uniformity and stability are correct, then

$$\partial A/\partial k = X$$

$$\partial A/\partial X = k$$

and

$$\delta k = 0$$

In this case we then have simply

$$k = \delta m/\delta X.$$

III. FAILURES IN THE MODEL

Not surprisingly, the conditions depicted in section II are extremely rare at most locations. The model can fail to adequately describe extinction for many reasons. A typical situation would be one in which perhaps 10% of the sky was covered with patchy thin clouds. In this case, $\partial A/\partial X$ is not simply k, but a highly complicated function of position. To illustrate the difficulties in determining the extinction, consider the case of k varying slowly with time. In this case we would have:

$$\delta m = X\dot{k}dt = k\delta X$$

If $\dot{k}dt$ can be kept small, then we can assume $\dot{k}$ is a constant and determine both k and $\dot{k}$ by observing two stars, one rising and one setting. However, small $\dot{k}dt$ will usually require small δX. But the uncertainty in k varies with $1/\delta X$; thus, for typical values of the uncertainty in m, keeping δX small ($\sim .2$), might yield a value for k like $0^{\text{m}}.27 \pm .^{\text{m}}23$, clearly a worthless determination.

Actually astronomers can often use nights on which the model fails as long as it does not fail too badly. There are two reasons for this. First, astronomers typically spend 10%-20%, occasionally more, of a night observing standards in order to accurately determine such numbers as k. Second, an unknown is typically observed several times during a night and the values obtained are averaged. Thus, a mean value for k can quite properly be applied to the observations. At the ETS, such a large fraction of time devoted to standards is highly undesirable. In addition, the individual observations will not generally be averaged, and so a mean value for k would not be appropriate. We can, thus, see that even under conditions which an astronomer might find

perfectly acceptable, the standard astronomical methods for correcting for atmospheric extinction may not be appropriate for the ETS.

The possibility of using a more complicated model must also be considered. One such model calculates absorption

$$A = kX = k'X^2.$$

Such a model (referred to as showing the Forbes Effect) is in fact physically expected and would be needed if unknowns were systematically lower in the sky than standards. Because observing time tends to increase as the square of the number of constants to be determined, the need for such a model at the ETS would be very unfortunate. Several series of measurements have been made at the ETS to determine k and k' with very poor results. This indicates that other failures of the model are more important, and the Forbes Effect may be neglected.

IV. THE ETS SOLUTION

Instead of starting with some model of the atmosphere and attempting to derive atmospheric parameters,we can simply write the absorption as a Taylor series about some point:

$$A = A_o + (\partial A/\partial X)_o \delta X + (\partial A/\partial k)_o \delta k + (\text{higher order terms})$$

As long as we can keep *both* δX and δk small, we may drop the higher order terms and make some simplifications.

$$A = k_o X_o + k_o \delta X + X_o \delta k \qquad (1)$$

$$= A_o + A_o/X_o \ \delta X + X_o \dot{k} \ \delta t \qquad (2)$$

$$= A_o (X/X_o) \qquad (3)$$

In going from equations (1) to (2), we are assuming no dependence of k upon azimuth and no discontinuities in A. In going from (2) to (3), we assume that we can make δt as small as we like.

Actually, equation (3) is a very unsurprising result, and one which merely gives us a way of extending an extinction measurement determined at one point to nearby points. It gives us no information about the atmosphere and still leaves us the problem of measuring A_o. We shall determine A_o by measurement of one or more known stars in the vicinity of the point of interest. Of course, the magnitudes of these stars must be known in the natural system of the equipment used. A catalog of such values has been prepared for the ETS. In essence, this approach allows us to carry out most of the observations of standards ahead of time. We can expect this approach to fail if it is not possible to keep δX and δt small.

It is interesting to make a comparison of the errors involved in this

technique with those involved in the standard astronomical method. The uncertainty in A_o is made up of the uncertainty in the catalog magnitudes, the uncertainty of a single observation, and the uncertainty in the zero point of the equipment. If the same piece of equipment is used to measure both stars and satellites, the zero point error affects both star and satellite measurement in the same sense, and so its effect is multiplied by δX, making it a negligible contributor. Since mean errors in catalogs and of a single observation both run about $0\overset{m}{.}03$, it should be easy to keep uncertainties due to atmospheric extinction at less than $0\overset{m}{.}05$. If this seems like surprisingly good accuracy for such a "rough and ready" technique, it should be noted that what is being done is essentially differential photometry.

On a night of excellent quality, the standard method is capable of even better accuracy. In this case, the uncertainty is the error in a single observation $\times\sqrt{(2 \div \text{number of observations})}$. This number can easily be made smaller than $0\overset{m}{.}02$. Consider, however, what happens on a night of lesser quality. Increasing value of $\dot{k}$ and increasing variation of k with X increase the uncertainty in the determination of k. More important, the value determined in a mean value of k over X and t, bearing an unknown relationship to the instantaneous local value sought. Of course, bad weather can adversely affect the determination of A_o, but the ETS method is resistant to weather effects in proportion to the ratios of the δX's and δt's in the respective methods. If a reasonable number of stars is contained in the catalog, δX and δt in the ETS determination will be about one-tenth of the corresponding values for the standard method.

V. THE REAL-TIME PACKAGE

Although it would be possible to do all the calculations of extinction, *etc.* after the fact, it is useful to have the information available more or less immediately, or, in computerese, in real-time. This would not be possible using the standard method. It is, however, possible with the ETS technique, and so we have designed a software package capable of performing equipment calibration, extinction measurement, and sky measurement on a real-time basis. The computer is used to control as much of the operation as possible, allowing the system to be run by comparatively untrained operators.

The software package described here deals with the acquisition of data, the software layout in conjunction with the real-time system, the operator interaction with the software, and the three types of photometry measurements. The measurements performed by the software are photometer calibration, local extinction, and night sky brightness. The software routines are designed to have minimum operator input and maximum computer control of operation.

Data from the photometer is received through an I/O channel at a 3ØHz interrupt rate with the data changing at approximately a 1ØHz rate. Each 16 bit word transmitted contains the BCD data and a flag, set on if the word is valid data. This somewhat cumbersome arrangement allows use of the existing TV-interrupt to read the asynchronous photometer. The interrupt for taking data is enabled by a push of console button "EXT". At each push, five seconds of data is read, sifted for those words with the flag set, converted to binary, and the mean and standard deviation calculated.

The extinction software routines are organized into three segments of

the real-time system: a level-2 overlay - EXTOV - with several subroutines to do mathematical calculation on the data, a task - LEF - to do local extinction star file setup, and a second task - SOIEXT - to enable the interrupt for taking data. Each of these segments is initiated by a button push. A star file of 323 stars has also been created containing the stars' right ascensions, declinations and magnitudes. This star file is stored on disk and is used by routines EXTOV and LEF in setting up subfiles of stars, also stored on disk, to be used for extinction data. It should be noted that the different software routines communicate among themselves and with other real-time system routines through dedicated global common regions.

The operator communicates with the software *via* the console ADDS and four console buttons labeled "SKY", "LEF", "SKIP STAR", and "EXT". The button labeled "SKY" can be considered a start-up button, to be pushed whenever the operator wishes to enter the extinction routine during real-time operations. S/He must then respond at the ADDS with the type of measurement desired: photometer calibration, local extinction, or night sky brightness. A push of button "LEF" is an indication to the software to search the main star file and create a subfile of stars to be used for local extinction measurements. The ten stars closest to the current telescope position meeting the specified requirements in right ascension, declination and elevation make up the local extinction file. "SKIP STAR" allows the operator to bypass taking data on a star if that data would produce erroneous results, *viz*, star is clouded over. "EXT" enables the interrupt for taking data as described previously. Messages on the ADDS cue the operator to push "EXT" at the appropriate times.

When the operator chooses to do photometer calibration, the first thing the software does is read the telescope position from global common. The main star file is then searched for calibration stars within 6 hours of right ascension from the current telescope position, above 18^{o} in elevation. The telescope is then sent to each of these stars sequentially by putting the star's right ascension and declination into global common. (The main pointing sequence of the real-time system is kept running during all extinction measurements, allowing for movement of the telescope while overlay EXTOV is active.) At each star, the operator can either skip the star by pushing the "SKIP STAR" button or take data by pushing the "EXT" button. Whenever the ratio of the standard deviation to the mean is too large, the data are rejected and the operator is cued to push "EXT" again. The operator must then move the telescope off the star onto a section of sky and again take data. This star-sky data collecting and processing is repeated until the star file is exhausted, at which time the zero point, Z, and mean extinction coefficient, K, are calculated using a linear least squares fit to the collected data. The values of Z and K are written to the console ADDS and line printer. The zero point value is stored in global common for later use in local extinction measurements. Overlay EXTOV then exits.

The steps involved in local extinction measurements are similar to those for photometer calibration with a few exceptions. The "LEF" button should have been pushed previous to entering the local extinction routine in order to set up the file of stars to be used in taking data. Using the LEF star file previously set up, the telescope moves sequentially to each star giving

the operator the choice of skipping the star or taking data. The photometry data zero point, Z, calculated during photometer calibration, star elevation, and magnitude are used in arriving at the local extinction coefficient, K. This process is repeated until three stars have been used for data collection or the star file is exhausted from pushes of the "SKIP STAR" button. When either of these two events occurs, the mean local extinction coefficient is written to the console ADDS and line printer, and the overlay exits.

To do night sky brightness measurements, the operator is instructed to take data on an area of the sky, producing a mean N_b. The operator then must cap the photometer and again push the "EXT" button, producing a mean value, N_d. The night sky brightness, m_b, is calculated from N_b, N_d, and the zero point, Z, calculated during photometer calibration:

$$m_b = 23.5 + Z - 2.5 \log(N_b - N_d).$$

The constant 23.5 contains the conversion to magnitudes per square arc second. The value for the night sky brightness is written to the line printer and console ADDS, and the overlay then exits.

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